RESOURCE COSTS OF SUPPLYING POWER TO A BATTLEFIELD

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Resource Costs of Supplying Power to a Battlefield

SUMMARY

This study develops and applies a general method for identifying the resources necessary to supply electric power to a battlefield. We refer here to power that is secured from a medium-sized source such as generators (gen-sets) and supplied to power-requiring devices such as communications gear; that is, power produced by one system and exported to another.[1] We propose such a method and apply it to a particular military unit, the Stryker Brigade Combat Team (SBCT), in two different scenarios, a long-term (1-year) mission and a short-term (1-month) version.

Traditionally, gen-sets and to a lesser degree auxiliary power units (APUs) located on vehicle platforms supply most battlefield electric power. Because considerable logistics resources are required to support gen-sets and the U.S. Army is looking to become leaner and more mobile, it is interested in alternative means of power supply, such as hybrid electric vehicles (HEVs) and under-the-hood power (UHP) systems.[2] One purpose here is to examine some of the conditions under which the HEV alternative is the superior choice.

Using our method, we first identify the resources involved in supplying power from gen-sets and then estimate the dollar cost per kilowatt-hour ($ per kWh) of doing so. The resources include gen-set depreciation and maintenance, fuel, personnel, backup power, and transport to and within a battlefield. We estimate the dollar cost of gen-set power so that we can compare such cost directly with that of other sources. We also examine gen-set cost drivers and find that more fuel efficient, reliable versions would significantly reduce these costs.

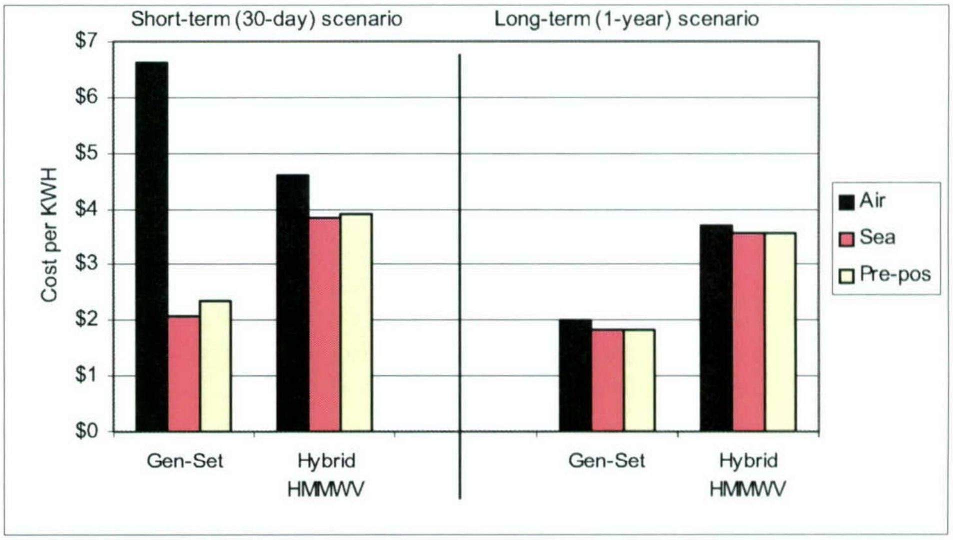
We next substitute export power from hybrid high mobility multipurpose wheeled vehicles (HMMWVs) for that from gen-sets. In a direct comparison of the support resource decrements and increments from the substitution, we see that weight and space are gained but costs are higher and mobility may be lost.

We then estimate power costs from the hybrid HMMWVs and compare them with those of gen-sets. Figure 1 shows such a comparison for both scenarios.

[1] Power from small-scale sources such as batteries is beyond the scope of this study.

[2] A hybrid electric vehicle combines an internal combustion engine with an electric motor and an energy storage source: batteries, capacitors, or both. Such a vehicle can be configured to export either direct current (DC) or alternating current (AC) power, but requires a converter to export the latter.

Figure 1. Estimated Power Costs from the Hybrid HMMWVs Compared with Those of Gen-Sets



As shown, costs per kWh are generally lower in the long-term scenario. In that scenario, per unit costs of power from HMMWVs are greater than those from gen-sets. However, in the short-term scenario, the comparison depends on the mode of transport used to move assets to the battlefield. If air is used, HEVs are the less costly option, but if sea or prepositioning is used, generators are less expensive.

Export power is but one feature of hybrid vehicles, however. Others include greater vehicle fuel economy, added range for a given amount of fuel, added transport capacity, the ability to run silently by drawing down from energy storage, and possible flexibility in vehicle design that allows for greater onboard payload. Thus, even in scenarios where export power from hybrid vehicles is more expensive than gen-set power, the tradeoff is added military utility.

A number of uncertainties underlie the analysis. These pertain to the battle scenario, Army planning factors, operating lifetimes of gen-sets and HMMWVs, and their maintenance costs. Our results would not be much affected by many of these, but some such as the scenario chosen do have important effects.

- Our approach to estimation of resources necessary to supply battlefield power applies to any medium-sized source and can be implemented for other forces and scenarios. With it, one can identify the support resources required by any power-exporting technology and can estimate its per-unit costs. Thus, we provide a means to compare a potential new source with gen-sets, hybrids, or any other existing power export system.

INTRODUCTION

This study develops and applies a method for identifying the resources necessary to supply electric power to a battlefield. We refer here to power that is secured from a medium-sized source such as generators and supplied to power-requiring devices such as communications gear, that is, power that is exported.[3] We describe and explain methods for estimating the resource cost of power exported via gen-sets and HEVs under varying conditions with respect to the mission.

Units engaged in battlefield operations require power for a number of applications, including radios and other communications devices, computers and peripheral equipment, climate control, radars, weapons, and many others. Commanders on the battlefield want power to be there when and where they need it and have little interest in the cost to get it there. But those responsible for ensuring such supply *do* need to understand the resources and logistics involved in making power available in order to find more efficient ways to provide it.

Our effort has a number of applications. First, the analysis indicates the full resource costs of projecting power onto a battlefield. We assess personnel, equipment, fuel, and other resources to fully account for what is required to meet unit power demands. Such information should help determine the importance of the logistics of power supply relative to other components of combat operations.

Second, the methods we describe can be applied under a variety of battlefield circumstances and for varied sets of forces. Thus, we provide a model for calculating the resource requirements for power supply that can be used for a variety of operational scenarios and for different mixes of forces.

Third, by identifying the main resource costs of power, we provide information potentially useful in designing new, cost-reducing technology. To reduce costs, it makes sense to aim at the main cost drivers.

Fourth, by estimating the cost of supplying power via one method such as generators, we provide a means to assess the potential gains from alternatives. In this study, we estimate the cost from a second alternative, HEVs, but other technologies—such as UHP power, APUs, and fuel cells—could be assessed as well.

Our findings indicate that power on a battlefield is substantially more costly than similarly produced power within the United States, a cost that should be reckoned in examining ways to curb the logistics of combat operations. The challenge for military planners is to find efficient means to provide forces in the field with power so that they are amply supplied but with a minimum of logistical support.

[3] In many cases, power is required but is supplied internally, within a system. For example, all vehicles require power to start and to run their internal equipment, but the batteries and generators onboard most of them fulfill this need.

Exposition

We begin by describing a pair of overseas combat scenarios to define the power required and the length of time.

We then present our basic model, which takes account of the various resources necessary to supply power to a battlefield. The model applies to any particular technology under which power is supplied.

Next, we apply the model to power supplied by tactical generators to an SBCT operating within our described scenario parameters. The application yields an estimate of the unit cost of power supplied through this technology to that force. We compare this unit cost to that of acquiring power similarly within the continental United States, that is, power acquired domestically through the use of generators.

We then vary assumptions regarding the scenario to see how power costs change. In particular, we test how the length of mission affects the cost of gen-set-delivered power.

Next, we estimate the cost of supplying power via HEVs to the same SBCT. We make a number of assumptions regarding power supplied via this technology to secure a range of estimates. In this analysis, we examine whether HEV power is competitive with gen-set in the long- and short-term scenarios and the main cost drivers.

Finally, we draw conclusions and describe areas where further research may prove fruitful.

Scenarios and Battle Unit

For purposes of analysis, we construct two scenarios, a long- and a short-term engagement. In the long-term scenario, we assume that U.S. forces engage overseas for a total of 1 year, in the following manner:

- The location is 8,700 miles from the United States (the planning factor for strategic deployment).
- U.S. forces maneuver while engaging the enemy for the first 30 days, traveling 2 hours and 30 miles each day. Export power is required 8 hours per day.
- Following the first 30 days, U.S. forces hold fixed positions for the rest of the year (335 days). Export power is required 16 hours per day. Transport vehicles are assumed to average 30 miles per day, ferrying soldiers, commanders, designated civilians, and others as needed.

The short-term scenario extends over only 30 days. We assume that it is made up of the first 30 days of the long-term scenario. The assumptions of the first 30 days remain the same as above.

These scenario descriptions have several implications for power-related resources. First, transport resources must be utilized to move power equipment to the point of engagement. Some of that equipment might be prepositioned near the theater of operation, but other might have to be flown or shipped by sea at the time of the engagement.

Second, mobility resources must be used to move power-exporting resources from one place to another on the battlefield. This might be done by air or by use of trucks, trailers, and forklifts.

Third, power-exporting equipment requires fuel, and we assume it is supplied wherever it is needed. This means that power-generating equipment must be supplied not only at the starting point of operations, but further out on the battlefield, perhaps several hundred miles away. It also means that equipment used to move gen-sets must be supplied with fuel for that purpose.

For the long-term scenario, the assumed utilization of power-exporting equipment implies that it would operate 5,600 hours,[4] while the operation itself would last 8,760 hours. In the short-term scenario, power-exporting equipment operates only 240 hours (30 days (8 hr/day), while the mission itself lasts 720 hours.

RESOURCES FOR GEN-SET POWER

We now analyze the resources required to project gen-set-supplied power onto a battlefield, and then estimate their dollar cost. We do so for an SBCT because it is the most modern Army fighting unit and its main means of supplying export power is through gen-sets. An SBCT is authorized by its table of organization and equipment (TOE) to carry 146 gen-sets in sizes varying from 2 to 60 kW. We identify the physical resources necessary to put these 146 gen-sets onto a field of battle and then estimate the associated costs.

Because power costs are usually expressed in $ per kWh, we calculate and express costs in this way. This gives us a basis of comparison among power sources, and between the cost to project power onto a battlefield and the cost within the United States. Once we are able to estimate an hourly cost of power, we can easily estimate the daily cost or any other multiple of interest.

Table 1 shows the cubic feet of space and weight of an SBCT's generators and trailers. We assume that all gen-sets 15 kW and above are trailer mounted, and those below are skid mounted, unless specifically designated otherwise. As shown

[4] (30 days at 8 hr/day) + (335 days at 16 hr/day).

in Table 1, an SBCT's gen-sets take up almost 18,000 cubic feet of space and weigh over 192,000 pounds, or 96 tons.

Table 1. SBCT Gen-Set Space and Weights

Type (kW)	Number	Space (ft^3)	Total weight (lb)
2	36	216	5,688
3	40	576	13,000
5	26	1,270	25,485
10	20	3,403	34,034
15	17	8,397	82,204
30	4	3,080	23,600
60	3	976	37,167
Total	146	17,918	212,962

Table 2 shows the ancillary resources necessary to fuel and sustain an SBCT's gen-sets on a battlefield. These include transport resources needed to bring the gen-sets to a theater and to move them from one place to another within it. We show C-17 air sorties necessary to bring the gen-sets, but sealift or prepositioning of this equipment could be used instead. Also, we show C-130 sorties necessary to move an SBCT's gen-sets or the number of 2.5-ton trucks it takes to carry or to tow the gen-sets from one battlefield spot to another. In addition, backup power, perhaps in the form of vehicle APUs, should be considered part of such resources.

Table 2. SBCT Gen-Set Ancillary Resources

Resource	Quantity
Fuel (per day)	2,616 gallons
Personnel (direct + indirect)	31
C-17 sorties	1.6
C-130 sorties	5.6
2.5-ton trucks (to carry 10 kW and smaller gen-sets)	25
2.5-ton trucks (to tow 15 kW and larger gen-sets)	24

GEN-SET POWER COSTS

Our cost model for power as applied to gen-sets is as follows:

$$\$ \text{ per kWh} = \frac{D + R + F + P + T_b + T_t + M + B}{k \times H},$$

where D = depreciation of gen-sets and accompanying trailers,

R = repair and maintenance parts and equipment,

F = fuel,

P = support personnel,

T_b = transport on the battlefield,

T_t = transport to the battlefield,

M = mobility,

B = backup power,

k = kilowatts of power capacity for an SBCT, and

H = hours of gen-set operation.

Appendix A details our approach to estimating the costs for each of these resource categories. Table 3 summarizes our estimates for an SBCT engaged in the long-term scenario.

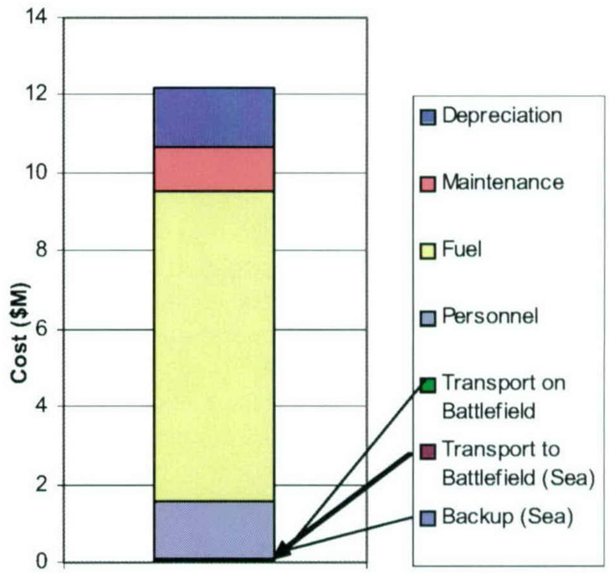
Table 3. Gen-Set Power Total Costs (SBCT Long-Term Scenario)

Category	Total cost ($000)
Depreciation	1,025–1,506
Maintenance	1,169
Fuel	7,935
Personnel	1,460
Transport on battlefield	81
Transport to battlefield	
Air	860
Sea	18
Preposition	98
Backup power	
Air	50
Sea	21
Preposition	22
Total	
Air	12,580–13,061
Sea	11,709–12,190
Preposition	11,790–12,271

The range of costs shown reflects differing assumptions about the operating life-time of this equipment. Also, we show costs for three different means of transporting gen-sets to the battlefield: air, sea, or prepositioning. Overall, the cost is roughly $12 to $13 million for supplying power to an SBCT for 1 year. Figure

2 shows the breakout of costs assuming the higher end of gen-set costs with transport by sea.

Figure 2. Breakout of Gen-Set Power Total Costs (SBCT Long-Term Scenario)



From Figure 2, fuel costs account for a very high proportion of gen-set costs, followed by depreciation, personnel, and maintenance. Transport and backup costs are negligible if sea transport is used. From this, improvements in fuel economy and maintainability would especially improve the competitive position of this power technology.

We now translate the total costs of power in Table 3 into a $-per-kWh charge for an SBCT. This will better allow us to compare this technology to others. The SBCT has 1,077 kW of power capacity, assumed to run for 5,600 hours, so the total capacity is 6,031,200 kWh. Table 4 shows per-kWh costs for the three different modes of transport.

Table 4. Gen-Set Power Unit Costs (SBCT Long-Term Scenario)

Transport mode	$/kWh
Air	2.08–2.16
Sea	1.94–2.02
Preposition	1.95–2.03

From Table 4, we estimate that the costs of supplying power via generators to an SBCT at a battlefield several thousand miles from the United States roughly lie between $1.95 and $2.15 per kWh.

How do these figures compare with the cost of supplying power within the United States? Clearly, one expects it to be more expensive to supply generator power overseas since it must be moved there along with fuel, personnel, and supplies.

Retail costs of electricity obtained from the grid run about $0.085 per kWh. However, the technologies used to provide grid power are quite different from those used in a military operation. A better comparison is the cost of gen-set-supplied power in the United States versus that for an Army operation overseas. (Appendix A describes an approach for estimating this cost.) In round terms, it costs about $0.40 per kWh to secure power from a gen-set in the United States, roughly one-fifth of the cost of generator-produced power in an overseas location far from U.S. shores.

Scenario Comparison

We are interested in whether the scenario we choose affects the cost of power. To find out, we now examine the behavior of power costs in our short-term scenario.

We assume the generators that accompany an SBCT are those the TOE designates, regardless of the mission. In the short-term scenario, they are used for 30 days × 8 hours = 240 hours. Table 5 compares the basic mission parameters.

Table 5. Scenario Parameters

	Short term	Long term
Mission duration	30 days	1 year
Gen-set operation time	240 hours	5,600 hours
Distance to theater	8,700 miles	8,700 miles

Many of the resources required to support power are reduced in this scenario. Depreciation of gen-sets and trailers, fuel required, and maintenance are lower. On the other hand, the transport resources and number of support personnel remain the same. Also, although the short-term scenario is only one-twelfth the length of the longer term, generators operate only about one-twenty-fifth as much. This is because they are assumed to operate more hours per day after intensive combat operations are completed, and we have cut out that portion of the mission. Table 6 shows the total costs for the short-term scenario.

Table 6. Gen-Set Power Total Costs (SBCT Short-Term Scenario)

Category	Total costs ($000)
Depreciation	44–65
Maintenance	47
Fuel	340
Personnel	122
Transport on battlefield	33
Transport to battlefield	
Air	860
Sea	18
Preposition	98
Backup power	
Air	32
Sea	2
Preposition	4
Total	
Air	1,479–1,500
Sea	607–628
Preposition	662–683

These costs are 7 to 10 percent of those of the long-term scenario, while the amount of power supplied is about 4 percent (1077 kW (240 hr = 258,480 kWh). Thus, while far fewer resources are utilized for power supply, the unit cost is higher (Table 7).

Table 7. Gen-Set Power Unit Costs (SBCT Short-Term Scenario)

Transport mode	$/kWh
Air	5.68–5.76
Sea	2.31–2.39
Preposition	2.52–2.60

From Tables 6 and 7, air transport to the battlefield is the largest single cost in this scenario and also raises the cost of gen-set power the most, relative to the long-term scenario. This occurs because air transport is much more expensive than sea or prepositioning and because transport to the battlefield is a fixed cost, so the shorter the mission, the higher the cost per kWh.

Mobility Constraint

In our scenario, we did not overlap power export with vehicle mobility needs—not much of a consideration when examining the cost of power from gen-sets. Gen-sets operate whether vehicles are being utilized at the time or not, so their needs generally do not conflict.

However, we later examine the implications of overlap when export power is obtained from HEVs, where the situation differs. When a vehicle is needed both for power export and for mobility, one constrains the other. This means that use of vehicles for power export purposes can have a cost in terms of mobility uses. We explicitly estimate this cost for a hybrid HMMWV below.

Advanced Gen-Set Technology

Table 3 makes it clear that fuel and, to a lesser extent, maintenance and personnel costs are the main drivers of power costs from gen-sets. Between them, they account for 80 to 90 percent of the total costs. This suggests that greater fuel economy and higher maintainability offer the best opportunities for significant reductions in the cost of power from this source.

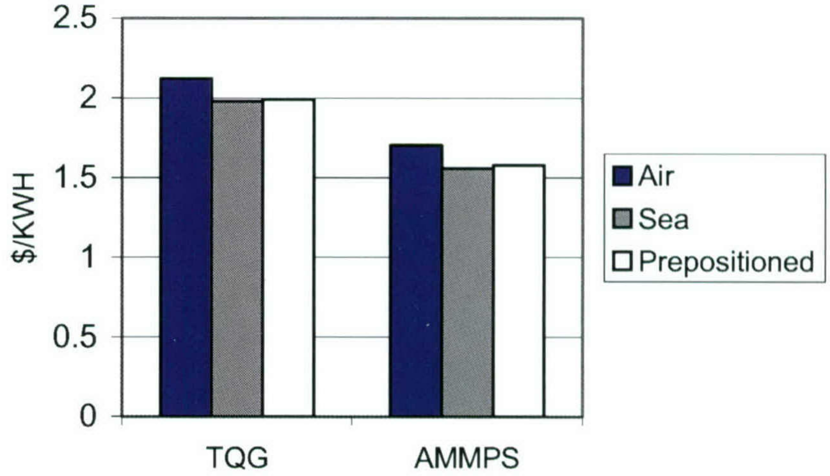
The Army has developed specifications for the next generation of gen-sets, called Advanced Medium-sized Mobile Power Systems (AMMPS). They specify substantial improvements in fuel economy and in mean time between failures (MTBF) for 5 to 60 kW gen-sets as well as weight and size decrements. Substantial improvements in fuel economy and maintainability would significantly affect the costs of gen-set-provided power. We substitute the proposed fuel economy and MTBF specifications of AMMPS for those of today's tactical quiet generators, add a 15 percent increment to acquisition cost, and reestimate the costs of supplying power through gen-sets (Table 8).[5] While costs per kWh are still well above those from gen-sets within the United States, they are some 20 percent less than today's gen-set technology on the battlefield and therefore, if achieved, would considerably increase the competitiveness of this power supply technology. The comparison is shown graphically in Figure 3.

Table 8. AMMPS Specification Cost per kWh

Transport mode	$/kWh
Air	1.65–1.74
Sea	1.52–1.61
Preposition	1.53–1.62

[5] See Appendix B for an explanation of the method.

Figure 3. SBCT Unit Costs of Power—AMMPS vs. TQG Technology



HYBRID ELECTRIC VEHICLES

We now apply our model to estimate the costs of supplying power to an SBCT in part from HEVs. This tests whether the model applies to a different source of power. It also shows the conditions under which the cost of export power from HEVs is competitive with that from gen-sets.

Military Advantages

HEVs offer many potential advantages to the military. Because they are capable of greater fuel economy than conventionally powered vehicles, they can conserve fuel for a given mileage traveled or achieve greater range for a given amount of fuel. The former saves on fuel, while the latter provides commanders in the field more mobility options. In addition, larger, more efficient hybrid transport vehicles could replace smaller conventionally powered ones and achieve more work for a given amount of fuel. This would allow, for example, fewer trucks to move a given amount of cargo in the field, conserving weight, space, and personnel needed for cargo transport purposes.

HEVs also are potentially capable of running silently by drawing on their energy storage systems for a time. This provides stealth capability while the vehicles are moving and a capability to conduct silent reconnaissance operations from a stationary position. These capabilities require adequate energy storage, however, a problem the military is working to overcome.[6]

Hybrid electrics offer certain attractive design features as well. A series hybrid has no transmission, and its electric motors can be placed in the wheel wells, conserving interior space. Also, its engine can be placed to maximize useful vehicle space. These features allow a series hybrid to carry a higher payload than a comparable conventionally powered vehicle.

Our interest in HEVs lies in their capability to export power and thus potentially to replace tactical generators. A major purpose of such substitution would be to reduce the logistics of supplying power to a battlefield, specifically transport resources to move power to the battlefield and to haul it within. Also, the planned Army of the future is highly mobile and largely self-sufficient in the early days of any combat action, and HEVs offer a means to secure needed export power during this time.

Finally, HEVs offer potential to supply very large amounts of power for very short periods. Pulsed power of this sort may be an efficient source for laser weapons, active vehicle defense systems, and other applications.

The extra hybrid capabilities would be limited by power export duties, however. If hybrid vehicles are used for power export much of the time, their other military advantages would have less utility. In other words, HEVs offer versatility, but devoting them to power export a significant portion of the time would greatly reduce the value of that versatility.

Substitution for Gen-Sets

A prototype hybrid HMMWV has demonstrated the capability to export 15 kW of power.[7] On this basis, we substitute hybrid HMMWVs with 15 kW of power export capability as prime power sources for 15 kW gen-sets within an SBCT. For such a substitution to be possible, a sub-unit of an SBCT must have both a 15 kW gen-set and a HMMWV assigned to it. Table 9 shows eight such substitutions given that constraint.

[6] Lead acid batteries have been used in hybrids but possess relatively low energy density and so are not well suited for stealth capabilities. Lithium ion batteries offer considerably better energy density but are much more expensive and require careful thermal management. Testing of prototype hybrid vehicles under operating conditions will be necessary to determine the extent to which they can supply stealth and silent watch capabilities in practice.

[7] The prototype hybrid has the capability to export up to 75KW of DC power. With auxiliary power systems, it can export more than 15KW of AC power, and a prototype has shown the capability to continuously export 33 kW. Potentially, such capability could be used to provide backup power on a battlefield.

Table 9. SBCT Sub-Units with 15 kW Gen-Sets and HMMWVs

Sub-unit	Number of gen-sets/HMMWVs
Headquarters and service battery field artillery battalion—operations section	3
Headquarters and distribution company brigade support battalion—repair parts section	1
Forward maintenance company brigade support battalion combat repair team	1
Forward maintenance co. brigade support battalion—wheeled vehicle repair section	1
Fwd maintenance company brigade support battalion—armament repair section	1
Fwd maintenance company brigade support battalion—missile/electric repair section	1
Total	8

Our assumed substitution is eight hybrid HMMWVs for three trailer-mounted 15 kW gen-sets and five 15 kW power units. In all, the assumed substitution covers 120 kW, or about 11 percent of the power supply of an SBCT.

Tradeoffs

Table 10 displays the tradeoff in power support resources. The decrement includes the gen-sets themselves, their maintenance, fuel, direct and indirect personnel, air sorties necessary to move them to and on the battlefield, and backup power. The increment for HMMWVs covers the same categories, including a mobility component to account for possible conflict between using vehicles for power export and mobility purposes.

Table 10 has several implications. HEVs have weight and space advantages over gen-sets. As a result, fewer resources are required to move them to the battlefield and within it. However, HEVs are more expensive to acquire and maintain, and more personnel are involved in their incremental maintenance and upkeep. Also, the time they spend exporting power may have a cost in terms of incremental vehicles required to maintain constant force mobility.

We assume that other resources, such as fuel consumption and backup power, are equal. We have some data to support the equal fuel efficiency assumption, but we assume equal backup power without the benefit of empirical evidence.

Table 10. Resource Tradeoffs

Category	Eight 15 kW gen-sets	Eight hybrid HMMWVs
Weight	35,740 lb	4,800 lb
Space	4160 ft^3	—
Acquisition cost	$170,400	$600,000
Maintenance	$11,100/yr	$19,200–$38,400/yr
Fuel	12 gal/hr	11-12 gal/hr
Personnel	1.7 soldiers	5.4 soldiers
Transport to battlefield (C-17 sorties)	0.3	0.04
Transport on battlefield (C-130 sorties)	0.9	0.12
Backup power	5 and 10 kW APUs	5 and 10 kW APUs
Mobility	—	Possible additional HMMWVs

While we have shown the tradeoff in C-130 assets needed to fly 120 kW of gen-set or HEV power from one point on a battlefield to another, we have not shown such a tradeoff for ground mobility resources. Hybrids would require no increment, but the freeing of trucks from towing 15 kW gen-sets could allow them to haul more other things or might allow an SBCT to get by with fewer trucks in total. A 15 kW power unit, for example, weighs over 5,000 pounds and might be towed by a 2.5-ton truck, whose onboard load is constrained by its trailer load. Without the power unit, more cargo could be stored onboard the truck, enabling fewer trucks in total to move an SBCT from one location to another. Thus, for example, if removing the eight 15 kW gen-sets enabled an SBCT to move the same total cargo as before with one fewer 2.5-ton truck, additional weight savings of over 13,000 pounds and space savings of 1,205 cubic feet.

Hybrid HMMWV Power Costs

Long-Term Scenario

We have shown that considerable logistics resources can be saved by reducing the number of 15 kW gen-sets assigned to an SBCT, but that hybrid HMMWVs also consume resources, perhaps as many or more. We now assess the costs of hybrid export power in our long-term scenario and compare it with that of comparably sized gen-sets.

Table 11 displays estimated costs of power for a single hybrid HMMWV capable of exporting 15 kW. Appendix C details the component estimates.

Table 11. Hybrid HMMWV Power Total Costs (Long-Term Scenario)

Cost Category	Amount ($000)
Incremental acquisition cost	92
Incremental maintenance cost	37–74
Fuel	99–109
Personnel	35
Transport on battlefield	Not applicable
Transport to battlefield	
Air	2
Sea	—[a]
Preposition	—[a]
Backup Power	
Air	6
Sea	3
Preposition	3
Mobility	
Air	54
Sea	12
Preposition	14
Total	
Air	325–372
Sea	278–325
Preposition	280–327

[a] Less than $500.

Table 12 translates these numbers into $ per kWh on the assumption that the vehicle produces 15 kW for 5,600 hours.

Table 12. Hybrid HMMWV Power Unit Costs (Long-Term Scenario)

Transport mode	$/kWh
Air	3.87–4.43
Sea	3.31–3.87
Preposition	3.33–3.89

From the numbers in Tables 12 and 4, export power from a single hybrid HMMWV is $1.35 to $2.25 per kWh more expensive than that from the complement of gen-sets of an SBCT. However, comparison of a single unit of one system with that of multiple units of another may well be misleading. Tables 13 and 14 make a more direct comparison, costing the eight hybrid HMMWVs and eight 15 kW gen-sets shown in Table 10 within the parameters of the long-term scenario for an SBCT. (Appendix D details the cost method.) Table 13 shows the total costs and Table 14 the per kilowatt hour costs.

Table 13. Power Cost for Eight Hybrid HMMWVs and Eight 15 kW Gen-Sets (Long-Term Scenario)

Cost category	HMMWVs ($000)	15 kW gen-sets ($000)
Depreciation	738	102–150
Maintenance and repair	295–590	165
Fuel	795–874	874
Personnel	267	80
Transport to battlefield		
Air	18	130
Sea	—	3
Preposition	1	10
Backup power		
Air	6	6
Sea	3	3
Preposition	3	3
Mobility cost		
Air	144	
Sea	60	
Preposition	65	
Total		
Air	2,276–2,650	1,357–1,405
Sea	2,171–2,545	1,227–1,275
Preposition	2,177–2,551	1,234–1,282

Table 14. Power Cost for Eight Hybrid HMMWVs and Eight 15 kW Gen-Sets ($ per kWh) (Long-Term Scenario)

Transport Mode	HMMWVs	Gen-sets
Air	3.39–3.94	2.02–2.09
Sea	3.23–3.79	1.83–1.90
Preposition	3.24–3.80	1.84–1.91

Tables 13 and 14 are revealing in several respects. Comparing like numbers of kilowatt capacity, we find that gen-sets are a cheaper means of providing power on the battlefield than are hybrid HMMWVs. They are cheaper to acquire and maintain, and they impose little or no mobility cost. Because they add weight and space, they are more expensive to transport to the battlefield (and more expensive to transport within the battlefield as well), but this increment is more than made up for by the other resource categories.

On the other hand, having to carry incremental weight and space can reduce a military unit's performance. Furthermore, gen-sets are less versatile than hybrid HMMWVs, without the potential additional military advantages. Thus, the long-term scenario produces a tradeoff: HEV export power is considerably more expensive, but an HEV offers other potential advantages that must be weighed.

SHORT-TERM SCENARIO

Table 15 compares the total costs of export power for eight HMMWVs and eight 15 kW gen-sets for the short-term scenario. In the short-term scenario, we do not impose a mobility cost on HMMWVs and we assume the same amount of backup power as for the long term. (Appendix D explains the calculations.)

Table 15. Power Cost for Eight Hybrid HMMWVs and Eight 15 kW Gen-Sets (Short-Term Scenario)

Cost category	HMMWVs ($000)	15 kW gen-sets ($000)
Depreciation	32	4–6
Maintenance and repair	13–25	7
Fuel	34–37	37
Personnel	22	7
Transport to battlefield		
Air	18	130
Sea	—	3
Preposition	1	10
Backup Power		
Air	4	4
Sea	—	—
Preposition	1	1
Total		
Air	124–139	191–193
Sea	102–117	60–62
Preposition	104–119	68–70

Over the 30-day period, eight 15 kW gen-sets or hybrid HMMWVs would export 8 (240 hr × 15 kW = 28,800 kWh. Table 16 shows the $-per-kWh costs.

Table 16. Power Cost for Eight Hybrid HMMWVs and Eight 15 kW Gen-Sets ($ per kWh) (Short-Term Scenario)

Transport Mode	HMMWVs	Gen-sets
Air	4.31–4.83	6.63–6.70
Sea	3.54–4.06	2.08–2.15
Preposition	3.61–4.13	2.76–2.43

Total costs of power are much less in the 30-day scenario, but unit costs are higher. Comparing unit costs, hybrid HMMWVs are the less expensive option if air transport is used, but gen-sets are less expensive if sea transport or prepositioning of equipment is used. A 30-day mission might often be associated with air transport, in which case hybrid export power would be the more cost-effective option even without the other potential military advantages. However, if sea transport or prepositioning are utilized, a tradeoff would remain between higher costs of HEV power export and the other potential capabilities derived from their use.

A key assumption in this scenario is that no mobility cost arises from the use of HMMWVs for power export, that is, they are not needed for mobility during the hours they are used for power export. Should this assumption not hold, the relative advantage of HMMWVs in the air transport scenario would diminish or disappear. The cost of transporting an incremental HMMWV 8700 miles by air is about $43,000. If only one extra HMMWV was needed, the cost of power from HMMWVs still would be less than that of gen-sets, but if two or more extra HMMWVs were required, gen-sets would be the less costly alternative.

OTHER TECHNOLOGIES

Several other means can supply power on a battlefield. APUs installed on vehicles can power onboard equipment or offboard systems through conversion to AC and a power distribution system. An APU can be particularly cost-effective as a substitute for a vehicle's primary power system when it is used to power auxiliary equipment while the vehicle is stationary. The Army currently fields 5 and 10 kW APUs in command and control vehicles and in standard integrated command post shelters (SICPS), respectively. As noted above, APUs also can be used as backup power, available for short periods while gen-sets or other power systems are being serviced or repaired.

Another option is to use a UHP system. These can take different forms, but basically involve using the belt-driven system on a vehicle and a converter/inverter to produce both DC and AC power, with an electronic control system to manage the power output. According to the Project Manager–Mobile Electric Power (PM-MEP), UHP is most effective in the 5 to 10 kW range, which makes it a good candidate for relatively small power export needs but less so for larger ones like major weapons systems. One possibility would be to use UHP as a substitute for an APU to power a SICPS.

APUs and UHP systems are much cheaper methods for producing export power than HEVs, but lack the military advantages that such technology offers. Also, like HEV technology, they require a vehicle to remain stationary when in power export mode, reducing its mobility capabilities.

Yet another option is to place power-requiring systems onboard platforms and supply them directly rather than through power export. Thus, for example, if a medical treatment center is incorporated onto a vehicle rather than set up as a separate shelter, climate control for that vehicle can come from the prime power source rather than through power export. Such placement also enhances the mobility of a force since systems that otherwise would have to be packed and unpacked instead can be carried as they are. On the other hand, putting systems onto a platform dedicates them to that platform, increases its weight, and requires an onboard power source that must operate whenever the systems are active. For a hybrid platform, for example, that may mean running the engine system a high percentage of the time. From our earlier estimates, this would increase the cost of supplying power relative to a separate (offboard) system powered by gen-sets.

CONCLUSIONS

In this study, we examine the resources necessary to supply power on a battlefield. We do so for a brigade-sized unit under two sets of operating conditions, long- and short-term scenarios.

One purpose is to establish a method for estimating the cost of power from any given source. We provide an accounting model that comprehends the resource categories needed to supply power and apply the model to tactical generators and to power export from HEVs. It appears that the model can be applied as well to other possible sources of power, APUs and UHP systems, for example.

Our compilation of the resources needed to support power from gen-sets on a battlefield suggests they are substantial and quite costly, around four to five times as much as gen-set power supplied within the United States. However, we compared the cost of gen-set power with that of export power from HEVs and found it is generally somewhat less. We also found that if a new generation of gen-sets now under development meets required specifications at acquisition costs no more than 15 percent above those of today's gen-sets, the per unit cost of power from this source will drop by around 20 percent.

The main drivers of the cost of supplying power on a battlefield are fuel and, to a lesser extent, personnel and equipment needed for maintenance and repair. This suggests that improvements to power supply systems should be aimed at improving their fuel economy and reliability, for example, by reducing their gallons/hour for given power output and by increasing their MTBF.

A number of uncertainties apply to our analysis. These include gen-set lifetime and maintenance requirements, hybrid HMMWV lifetime and acquisition and maintenance costs, and combat scenario parameters. The uncertainties are discussed and some of their impacts on cost estimates quantified in Appendix E.

The results of our tradeoff analysis between gen-sets and HEV power are not as strong as we would desire; although considerable data are available on the performance and cost of gen-sets, relatively little is available on the performance of hybrid vehicles in power export mode. The Army's development of hybrids has proceeded in fits and starts, so that compilation of more such data will take time. As future forces are counting on hybrid vehicles as sources of power, the building and testing of prototype models should proceed as rapidly as possible.

Appendix A. SBCT Gen-Set Power Cost

Basic Model

Our cost model for power applied to gen-sets is as follows:

$$\$ \text{ per kWh} = \frac{D + R + F + P + T_b + T_t + M + B}{k \times H},$$

where D = depreciation of gen-sets and accompanying trailers,

R = repair and maintenance parts and equipment,

F = fuel,

P = support personnel,

T_b = transport on the battlefield,

T_t = transport to the battlefield,

M = mobility,

B = backup power,

k = kilowatts of power capacity for an SBCT, and

H = hours of gen-set operation.

We proceed to estimate each of these elements for the long-term scenario and then summarize them for the short term.

Gen-Set Depreciation

Generators produced for the military tend to be more expensive than comparable commercial generators because they must meet more rigorous standards. Also, military gen-sets are built to run on JP-8, the standard military fuel, whereas many commercial generators run on gasoline, which is more easily obtainable within the continental United States.

Gen-sets can be wheeled or skid mounted, or mounted on trailers for purposes of transport. Smaller skid-mounted gen-sets, 2 or 3 kW in capacity, can be lifted and taken down from the beds of trucks by groups of soldiers, but larger gen-sets, 5 kW or more in capacity, either must be lifted and taken down by forklift or put on a trailer and left there.[1] Putting and leaving larger gen-sets on trailers save time

[1] A 5 kW, 60 Hz, skid-mounted gen-set weighs 888 pounds.

and soldier effort in the field, but flexibility is lost if this is done. How gen-sets are dealt with in the field depends on several things, including the maneuverability of the particular unit, the availability of transport resources such as forklifts, and other factors. For present purposes, we assume that only gen-sets of 15 kW and more are trailer mounted.

According to a recent study, gen-sets have a 17-year life and their historic average usage is 375 hours per year.[2] This equates to lifetime usage of 6,375 hours. However, according to a knowledgeable source, in practice Army budget limitations have extended the replacement cycle for gen-sets closer to 25 years.[3] Over a 25-year life, at 375 hours per year, the total usage would be 9,375 hours.

Table A-1 shows the per unit and total costs of gen-sets and trailers for an SBCT.

Table A-1. SBCT Gen-Set and Trailer Cost

Gen-set type	Number	Trailer type	Per-unit cost ($)	Total cost ($)
2 kW skid	36	None	6,000	216,000
3 kW skid	40	None	9,205	368,200
5 kW skid	25	None	8,145	203,625
5 kW PP mt	1	Single unit	33,085	33,085
10 kW Skid 60 Hz	12	None	6,979	83,748
10 kW Skid 400 Hz	1	None	15,304	15,304
10 kW PU mt 60 Hz	6	Single unit	17,730	106,380
10 kW PU mt 400 Hz	1	Single unit	30,000	30,000
15 kW skid + tr	1	2.5 ton	16,160 + 34,569	50,729
15 kW PU mt	11	Single unit	19,080	209,880
15 kW mt	5	Single unit	25,000	125,000
30 kW PU mt	4	Single unit	28,521	114,084
60 kW 60HZ skid + tr	1	2.5 ton	25,073 + 34,569	59,642
60 kW 400 HZ skid + tr	1	2.5 ton	28,425 + 34,569	62,994
60 kW PU mt	1	Single unit	35,000	35,000
Total	146	—	—	1,713,671

Note: PU = power unit (a single gen-set on a trailer); PP = power plant (two gen-sets on a trailer, one for backup); mt = trailer mounted; tr = trailer; Hz = hertz.

The total shown in Table A-1 is the acquisition cost of gen-sets and accompanying trailers for an SBCT. If gen-sets and their trailers have a lifetime of 6,375 hours, then the depreciation rate is $269 per hour. However, if that lifetime is 9,375 hours, then the rate is $183 per hour. For purposes of exposition, we henceforth assume an operating life of 9375 hours.

[2] U.S. Army, "Power Assessment for IBCT," Version 1.0, Project Manager–Mobile Electric Power (PM-MEP), Fort Belvoir, VA, November 30, 2001, p. 4.

[3] Dr. James Cross, Deputy Project Manager, PM-MEP, personal communication, February 4, 2004.

With this calculation, we see that while the hourly depreciation rate is constant over the lifetime of an SBCT's gen-sets, the daily or weekly rate varies with the intensity of use. For example, during the initial segment of our assumed long-term operation gen-sets are used 8 hours per day, so that the daily rate of depreciation is $1,464. However, during the second segment, they are run 16 hours per day, so the daily cost rises to $2,928. Overall, over the 365-day long-term engagement the SBCT's gen-sets would run for 5,600 hours or between 60 percent of their expected lifetime, and the total depreciation, *D*, over that period would be around $1 million.

Maintenance

Maintenance involves repair plus preventive and ongoing maintenance. Inputs include lubricants, coolants, filters, spare parts, and tools and equipment used for purposes of cleaning and servicing.[4]

The Army's Operational Requirements Document for Tactical Electrical Power (ORD-TEP) contains data on the cost of maintaining 5 to 60 kW gen-sets, based on a 300 hour per year operating schedule.[5] We extend these data to 2 kW and 3 kW sizes in order to estimate maintenance costs for all of the gen-sets of an SBCT, adjust the numbers to remove labor costs,[6] and increase them to account for a 375-hour year. For estimation purposes, we assume that annual maintenance costs for 2 kW and 3 kW gen-sets are proportional to those for 5 kW, labor costs are 20 percent of maintenance costs,[7] and that these costs rise linearly if the gen-sets are run 375 rather than 300 hours per year.[8] Table A-2 shows annual maintenance costs under these assumptions.

Table A-2. Annual Gen-Set Maintenance Costs

Gen-set size (kW)	Annual cost ($)	Gen-set size (kW)	Annual cost ($)
2	217	15	1,383
3	325	30	1,179
5	542	60	1,648
10	512	—	—

[4] We treat maintenance personnel separately, specifically by accounting for personnel assigned to generator maintenance and repair within the SBCT by its TOE.

[5] ORD-TEP, November, 2003.

[6] We do this to avoid double-counting since we estimate personnel costs directly from the SBCT TOE.

[7] Data covering over 3,000 gen-set work orders indicate that labor costs account for just under 20 percent of scheduled and unscheduled maintenance costs.

[8] The data from the ORD-TEP indicate that gen-set maintenance costs are not proportionate to gen-set size and do not indicate whether costs rise proportionately with hours of use. However, because maintenance costs are a relatively small part of gen-set costs, any bias introduced through our proportionality assumptions likely is very small.

Given these values and the makeup of an SBCT's 146 gen-sets, their aggregate annual maintenance cost at 375 hours of use per year is $78,315, or $209 per hour. If they are operated for 5,600 hours per our long-term scenario, the total cost of maintenance, *M*, would be $1.169 million.

Fuel

The movement of fuel to a battlefield requires ships, personnel, and a good deal of equipment. Previous work has estimated that it costs $13 per gallon to place fuel at the staging point in a theater, and more to move it further.[9] We use the $13-per-gallon estimate in our analysis. Thus, the hourly cost of fuel for any given gen-set is the product of the number of gallons per hour it consumes and $13.[10]

Given the rates of fuel use of the individual generators within an SBCT, collectively they utilize 109 gallons per hour. At $13 per gallon, the total cost of fuel if all 146 generators operate at capacity is $1,417 per hour. If gen-sets at op tempo run 8 hours per day for the first 30 days and 16 hours per day after that, the total cost, *F*, over a 1-year operation would be almost $8 million.

Personnel

The tables of organization and equipment (TOEs) for individual units assign certain personnel to the maintenance and repair of generators. They are listed under Military Occupational Specialty (MOS) 52D10, which pertains to power generator equipment representatives or supervisors. These soldiers carry out preventive and scheduled maintenance and are responsible for repairs when gen-sets break down.

Within an SBCT, 12 soldiers (out of about 3,600 authorized) are designated to maintain 146 gen-sets.[11] These soldiers likely do other things as well, such as maintain climate control or other equipment. However, other soldiers operate generators, secure spare parts, arrange for or provide transport, help load and unload the gen-sets, and construct noise-suppression berms around them. In addition, the TOE contemplates peacetime as well as combat operations, and much more intensive use of gen-sets is likely in a combat setting. For all these reasons,

[9] Defense Science Board (DSB), *More Capable Warfighting Through Reduced Fuel Burden*, May 2001, p. 19. The DSB cites the Army Research Laboratory as the original source of this number, and proceeds to estimate the cost of moving fuel from an initial base point out onto a battlefield. Depending on the mode of transport and the distance, these costs range from a few dollars to several hundreds of dollars per gallon.

[10] News reports from Iraq indicate that after Operation Iraqi Freedom was completed, fuel could be obtained at much lower costs, in the range of $1.25–$2.25 per gallon. However, these are not wartime costs. Furthermore, they are only purchase costs, not those of the underlying military supply network in place to acquire and ship fuel as needed. The DSB report cited in Note 9 stresses that purchase costs are but a fraction of the total cost of supplying fuel to a battlefield.

[11] For comparison purposes, 31 soldiers are assigned to maintain generators in a separate heavy mechanized infantry brigade.

we assume the MOS designation is a reasonable approximation for labor associated with gen-sets within an SBCT.

We also account for support personnel for the 12 soldiers. By that, we refer to cooks, chaplains, medical personnel, administrators, military police, and the like. Within an SBCT, the ratio of support to combat personnel is 1:6.[12] This implies that there are 2 support personnel within the SBCT. Furthermore, within the deployable portion of the Army, about 1 in 3 personnel are in echelons providing combat service support (a ratio of 1:2).[13] From this, another 7 personnel can be attributed to SBCT gen-set support,[14] for a total of 21 soldiers. Similarly, on average for every deployable member of the Army, there is another 0.5 non-deployable in the United States (again a ratio of 1:2).[15] Using this average ratio, we add another 10 support personnel. In total, 19 personnel support the 12 SBCT gen-set operators, or 31 personnel in all.

We assume operators and drivers in the field are paid \$39,000 per year (about the pay and benefits of an E-3). For support personnel, we use the all-Army average pay in FY02 of \$52,200.[16] Thus, for the long-term mission, the cost of personnel associated with SBCT gen-sets, the variable P, is $12 \times \$39,000 + 19 \times \$52,200$, which equals around \$1.46 million.

Transport on Battlefield

Resources such as airplanes, trucks, and trailers are utilized to transport gen-sets from one location to another on a battlefield. However, in our operational scenario there is no air transport within the battlefield, so we focus instead on ground transport.

In the scenario, smaller gen-sets, up to 10 kW, are assumed carried on the backs of trucks, while larger sets are transported via trailers hooked up to HMMWVs or larger trucks. For present purposes, we assume transport vehicles are not diverted from alternative use in the sense that they are not forced to forego other duties when they are used to haul gen-sets. In reality, there could be conflicting uses during such time, and, if so, transport would have a cost in terms of foregone mobility.

[12] Some judgment is required to identify who is support and who is not. As a working definition, the brigade support battalion and the brigade HQ are considered support, while the other units within an SBCT are considered fighting units. By this definition, 509 of 3,614 personnel within an SBCT are support, from which we calculated the ratio of 1:6.

[13] In 2002, Army TOEs identified a little over 200,000 soldiers as belonging to combat forces (divisions, brigades, etc.) and another 100,000 or so to support forces.

[14] Six for the 12 support personnel and another one for the 2 indirect.

[15] The deployable portion of the Army is defined as those identified in TOEs as deployable, while the non-deployable portion is those identified in tables of distribution and allowance (TDAs) as non-deployable. By this definition, in 2002 the deployable Army consisted of 317,077 positions, and the non-deployable consisted of 161,769, almost exactly a 2:1 ratio.

[16] The President's Budget, FY04–09 Future Years Defense Programs, March 2003.

However, we focus instead on the direct costs of cargo carriage necessary to accommodate the weight and cube of gen-sets and their associated equipment (such as power distribution lines, auxiliary power distribution systems, and gen-set covers). The trucking resources required to bear the weight and cube of the gen-sets and associated equipment are an input into the export of power on a battlefield.

Our analysis indicates that weight is the binding constraint.[17] Under our assumption that all of the gen-sets of an SBCT up to 10 kW in capacity are carried on the backs of trucks, the total weight of this cargo is 56,292 pounds. We add 10 percent to account for associated equipment, yielding an overall estimate of 61,921 pounds. This implies that it requires the equivalent of twenty-five 2.5-ton trucks to haul this cargo on a battlefield.

A 2.5-ton truck costs around $42,000. The average U.S. Army truck operates only about 3,000 hours over its lifetime, which implies a depreciation rate on a 2.5-ton version of $14 per hour. It also seems reasonable to attribute another $24,000 in lifetime operations and maintenance (O&M) costs to this vehicle, which would be an additional $8 per hour. Thus, the estimated hourly cost of using a 2.5-ton truck during combat operations is $22 per hour.

In addition, there is the cost of fuel needed to move the gen-sets. U.S. forces are assumed in our op scenario to move 30 miles per day over 2 hours. If a 2.5-ton truck achieves 7.5 mpg, then each truck carrying the smaller gen-sets would use 2 gallons per hour, which at $13 per gallon would be $26 per hour. In addition, trucks towing the larger (15kW and above) gen-sets would suffer some reduction in fuel economy. We assume these trucks would achieve 6 mpg instead of 7.5 mpg, so that each would consume an extra .5 gallon per hour. This adds another $6.50 per hour.

With these data, we can sum up the motor transport cost of gen-sets on a battlefield. The cost per hour is $22 + $26 = $48 per 2.5-ton truck. Each of those 25 trucks is utilized for 2 hours per day for 30 days, so the total for them is $48 × 25 × 30 × 2 = $72,000. Another 24 trucks are engaged in pulling 15kW and larger gen-sets, and the fuel penalty for them is $6.50 x 24 x 30 x 2 = $9,400. Adding the two, the total of $81,400 is a fixed cost of on-battlefield gen-set transport for an SBCT for this particular operation.[18]

[17] A 5-ton truck has 30.5 cubic yards of carrying capacity. By cube, this would be sufficient to carry all of the 2 and 3 kW gen-sets of an SBCT. By the weight of these gen-sets, however, three such trucks would be required.

[18] Using C-130 assets to move gen-sets from one part of a battlefield to another costs much more.

Transport to Battlefield

There are several choices regarding how gen-sets can be moved to a theater. They can be airlifted from the United States (by far the most expensive), sea-lifted, or prepositioned in the vicinity of the theater and then air- or sea-lifted from there. We estimate the cost of moving gen-sets and 21 deployed personnel by all three of these methods, providing a wide range of transport costs. We also allocate a small portion (2%) of the cost of moving 25 2.5-ton trucks and their drivers to the theater, since these would be used for gen-set transport for 60 hours but much more for other purposes during a year-long mission.

According to our scenario, action takes place 8,700 miles from the United States. We use standard current military rates per ton mile or per ton for air and sea lift:

- Air: $0.856/ton mile
  $0.2268/pax mile
- Sea: $35.88/metric ton—loading
  $114.71/metric ton—shipping
  $25.50/metric ton—discharge.

The total cost of transport by sea is the sum of the loading, shipping, and discharge costs, or $176.09 per metric ton. This equates to $160.26 per short ton.

Finally, we estimate the cost of prepositioning near a theater. We do not have cost data for forward storage depots or for floating storage. In U.S. metropolitan areas, storage costs run several dollars per square foot per month, but in more rural areas the costs are less. We assume storage can be obtained where real estate is inexpensive or on shipboard at $1 per square foot per month. We suppose the gen-sets and vehicles are shipped by sea to the forward storage area, stored for 1 year prior to engagement, and then transported 500 miles to the theater by air.

Under the above assumptions, we derive the cost numbers shown in Tables A-3, A-4, and A-5.

Table A-3. Air Transport Costs for SBCT Generators

Category	Weight (tons)/number	Cost ($)
Generators + trailers	106.5	793,100
Passengers	21 deployed soldiers	41,400
Trucks + drivers[a]	163.2 tons/25 soldiers	25,300
Total		859,800

[a] 2 percent of total cost.

Table A-4. Sea Transport Costs for SBCT Generators

Category	Weight (tons)/number	Cost ($)
Generators + trailers	106.5	17,100
Passengers	21 deployed soldiers	300
Trucks + drivers[a]	163.2 tons/25 soldiers	500
Total		17,900

[a] 2 percent of total cost.

Table A-5. Transport Costs with prepositioning of SBCT Generators

Category	Weight (tons)/space (ft^2)/number	Cost ($)
Generators + trailers (weight)	106.5 tons	62,700
Generators + trailers (storage space)	2,472 sq ft	29,700
Personnel	21 deployed soldiers	2,700
Trucks + drivers[a]	163.2 tons/4,400 sq ft/25 soldiers	3,000
Total		98,100

[a] 2 percent of total cost.

Thus, our values for the variable, T_b, are \$859,800, \$17,900, and \$98,100. These are fixed costs in that they do not vary with the length of mission nor the intensity of gen-set use.

Mobility

We assume that SBCT mobility assets used to move gen-sets on a battlefield are not prevented thereby from carrying out their other mobility duties. For that reason, we include no cost term for mobility for the gen-sets of an SBCT.

Backup Power

We assume the gen-sets of an SBCT provide power throughout the mission. We allow for maintenance and repair, but do not explicitly account for gen-set attrition and downtime, though some is likely to occur. To reflect this, we include a backup power term, which can refer to APUs or gen-sets that are not used except if the primary sets go down.[19] Since only one or the other is used at any given time, aggregate depreciation calculated on the basis of use does not change. However, there is a cost of tying up capital plus costs to transport the backup power to the battlefield and move it around there.

[19] Power plants would be one option. They involve two gen-sets on the same trailer platform, with one used when the other is down. An SBCT is assigned one 5 kW power plant but, for weight and space considerations, is likely to use APUs for most of its backup power.

For present purposes, we assume ten 5 kW and ten 10 kW APUs are used to provide 100 kW of backup power.[20] A 5 kW APU costs $16,342 and a 10 kW $20,400, so their aggregate cost is $285,710. At a 7 percent cost of capital, this would be $20,000 per year.

The aggregate weight of this backup power is 8,045 pounds. Given costs of air, sea, and prepositioning as stated above, the cost of transport would be $30,000 by air, $600 by sea, and $2,400 with prepositioning. Thus, for the long-term engagement, the total costs of backup power would be $50,000 if transported by air, $20,600 if by sea, and $22,400 with prepositioning.

Summary

We can now estimate the total cost of supplying power to an SBCT for one year (Table A-6).

Table A-6. Summary of Cost Elements for SBCT Generator Power

Category	Total cost ($000)
Depreciation	1,025
Maintenance	1,169
Fuel	7,935
Personnel	1,460
Transport on battlefield	81
Transport to battlefield	
Air	860
Sea	18
Preposition	98
Backup power	
Air	50
Sea	21
Preposition	22
Total	
Air transport	12,580
Sea transport	11,709
Preposition	11,790

Finally, we translate these hourly costs of power into a $-per-kWh charge for an SBCT per our basic equation. The value of K for an SBCT is 1,077 kW of power capacity, and the value of H is 5,600 hours under our assumed mission profile, so the total power output is 5,600 hr × 1,077 kW = 6,031,200 kWh. Table A-7 shows unit costs for the three different modes of equipment transport.

[20] According to its TOE, an SBCT has a total of 27 10KW APUs and 36 5KW APUs assigned to it.

Table A-7. Gen-Set Power Unit Costs (SBCT Long-Term Scenario)

Transport mode	\$/kWh
Air	2.08
Sea	1.94
Preposition	1.95

Summarizing the data in Table A-7, we estimate that the costs of supplying power via generators to an SBCT at a battlefield several thousand miles from the United States roughly lie between \$1.95 and \$2.10 per kWh.

We can make an approximate comparison to the cost of producing power from gen-sets within the United States. In Washington, DC, one can rent a 5 kW generator for about \$570 per month. If the generator is operated 16 hours per day for 30 days and consumes 1/2 gallon of fuel per hour at \$2.00 per gallon, then its total costs (ignoring transport) are \$570 + \$480 per month, or about \$1050 per month. Given that it provides 5 kW × 16 hr/day × 30 days = 2400 kWh, the average cost would be about \$.44 per kWh. Evidently, it is four to five times as expensive to provide generator-produced power in an overseas location far from U.S. shores.

Short-Term Scenario

The short-term scenario consists of the first month of the long-term scenario. We assume the generators that accompany an SBCT remain those designated for it by its TOE regardless of the length of the mission. In this scenario, they are used for 30 days × 8 hr/day = 240 hours.

The resources required to support power are reduced in this scenario. There is less depreciation of gen-sets and trailers, less total fuel required, and less maintenance. On the other hand, transport resources and the number of support personnel remain the same. Also, while the short-term scenario is about 8 percent the length of the long term, generators operate only about 4 percent as much. This is because they are assumed to operate more hours per day after intensive combat operations are completed, and we have cut out that portion of the mission. Table A-8 shows total costs for the short-term scenario.

Table A-8. Gen-Set Power Total Costs (SBCT Short-Term Scenario)

Category	Total costs ($000)
Depreciation	44
Maintenance	47
Fuel	340
Personnel	122
Transport on the battlefield	33
Transport to the battlefield	
Air	860
Sea	18
Preposition	98
Backup power	
Air	32
Sea	2
Preposition	4
Total	
Air	1,479
Sea	607
Preposition	662

These costs are 7 to 10 percent of those of the long-term scenario, while the total power supplied is only about 4 percent. Thus, while far fewer resources are utilized for gen-set power supply, the unit cost is quite a bit higher (Table A-9).

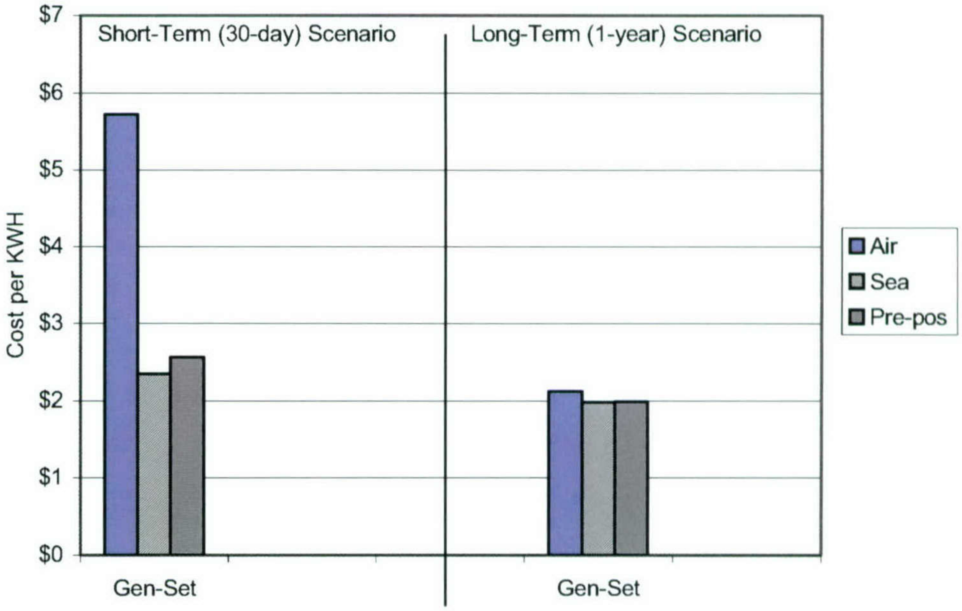
Table A-9. Gen-Set Power Unit Costs (SBCT Short-Term Scenario)

Transport mode	$/kWh
Air	5.68
Sea	2.31
Preposition	2.52

As seen in the table, the cost of gen-set power rises most for air transport to the theater. This occurs because air transport is much more expensive than sea or prepositioning and because these are fixed costs, so the shorter the mission the higher the cost per kWh.

Per unit gen-set power costs are shown graphically in Figure A-1. The strongest inferences are that gen-set power is much more expensive per unit if air rather than sea transport or pre-positioning is used for a short combat operation, and that such power is less expensive if the operation is of longer duration.

Figure A-1. Per kilowatt Hour Costs of Power from Gen-Sets



APPENDIX B. AMMPS POWER COSTS

The specifications for Advanced Medium-sized Mobile Power Systems (AMMPS) gen-sets require significant increases in fuel economy and Mean Time Between Failure (MTBF), plus a reduction in weight and size. In terms of our power cost model, these will affect the cost of fuel, F; the cost of personnel, P; the cost of maintenance, M; transport to the battlefield, T_t; and transport within the battlefield, T_b. Because these gen-sets are likely to be more costly than present versions, we assume a 15 percent increase in depreciation costs.[1]

Table B-1 shows the fuel economy specifications for Tactical Quiet Generators (TQGs) and for 5 to 60 kW AMMPS gen-sets. If the AMMPS specifications are realized, the gen-sets of an SBCT would reduce their consumption of fuel from 109 to 81gallons per hour. At $13 per gallon and 5,600 hours, the total cost of fuel, F, would decrease from $7,935,200 to $5,896,800.

Table B-1. Fuel Economy Specifications for TQG and AMMPS Gen-Sets (Gallons/Hour)

Gen-set (kW)	TQG	AMMPS
5	0.57	0.39
10	0.97	0.63
15	1.50	1.04
30	2.43	1.56
60	4.51	2.79

In Table B-2 below, we show the specifications for increased MTBF for AMMPS gen-sets. These increases range from as low as 25 percent for the 30 kW 60 Hz model to 70 percent for the 5 kW 60 Hz. Taken as a whole, the specifications call for increases of around 50 percent over present hourly rates of failure.

Table B-2. MTBF Specifications for AMMPS and TQGs (Hours of Operation)

Gen-set	TQG	AMMPS
5 kW 60 Hz	442	750
10 kW 400 Hz	462	750
15 kW 60 Hz	538	750
30 kW 60HZ	600	750
60 kW 60 Hz	488	750

[1] No contracts have yet been awarded for AMMPS gen-sets, but preliminary information indicates that this is the rough magnitude of expected increases in acquisition costs (personal communication from Mr. Tim Raney, CASCOM DCD Ordnance, April 16, 2004).

Increases in MTBF of this magnitude should decrease maintenance and personnel requirements because fewer repairs should be needed. We assume therefore that maintenance costs and personnel needed for maintenance and repair purposes would decrease by 25 percent. The decrease in direct personnel implies comparable decreases in indirect personnel.

Table B-3 shows the weight specifications for AMMPS gen-sets compared with TQGs.

Table B-3. Weight Specifications for AMMPS and TQG (Lb)

Gen-set	TQG	AMMPS (objective)
5 kW	888	665
10 kW	1,182	950
15 kW	2,124	1,650
30 kW	2,931	2,050
60 kW	4,063	2,950

The AMMPS specifications would reduce gen-set weights by 20 to 25 percent relative to TQGs. This would reduce the resources necessary to transport generators to a battlefield and within it.

Table B-4 shows how, under our long-term scenario assumptions, resource costs of gen-set power delivered to a battlefield would be affected by achievement of the AMMPS specifications. As indicated above, we increase depreciation rates by 15 percent to reflect the increase in projected acquisition costs. The cost comparison is also shown in Figure B-1. Both Table B-4 and Figure B-1 indicate that depreciation, maintenance, personnel and especially fuel costs dominate total gen-set costs. Transport (by sea) and backup costs are too small to have much effect.

Table B-4. Costs of TQGs and AMMPS Gen-Sets ($000)

Resource category	TQG	AMMPS
Depreciation	1,025	1,179
Maintenance	1,169	877
Fuel	7,935	5,897
Personnel	1,460	1,095
Transport on battlefield	72	60
Transport to battlefield		
Air	834	781
Sea	17	16
Preposition	95	92

Table B-4. Costs of TQGs and AMMPS Gen-Sets ($000) (Continued)

Resource category	TQG	AMMPS
Backup power[a]		
Air	50	50
Sea	21	21
Preposition	22	22
Total		
Air	12,545	9,939
Sea	11,699	9,145
Preposition	11,776	9,220

[a] We assume costs of backup power remain constant over time because we have no information on future specifications for APUs.

Figure B-1. Breakdown of Total Costs of TQGs and AMMPS Gen-Sets

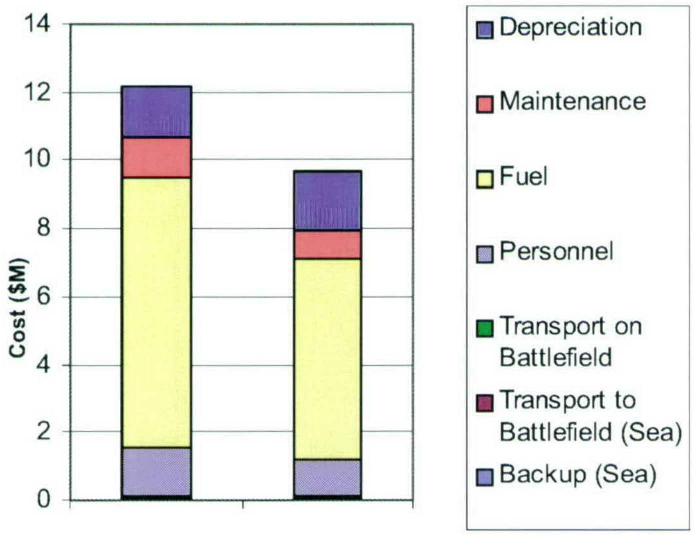


Table B-4 and Figure B-1 indicate that total costs of gen-set power for an SBCT would drop by about $2.5 million with the use of AMMPS. Table B-5 translates this into $ per kWh. In round numbers, power costs would drop from $1.95–$2.10 per kWh to around $1.55–$1.65 per kWh, still much more than domestic power from gen-sets, but a significant decrease nonetheless. The AMMPS specifications may be challenging, but if they can be achieved at a 15 percent increase in gen-set acquisition cost, they would substantially improve the competitive position of this technology relative to other possible sources of battlefield power.

Table B-5. SBCT Unit Costs of Power—AMMPS v. TQG Technology ($/kWh)

Transport mode	TQG	AMMPS
Air	2.08	1.65
Sea	1.94	1.52
Preposition	1.95	1.53

Appendix C. Hybrid HMMWV Power Costs

Cost Model

In this appendix, we estimate the cost of export power for a single hybrid HMMWV. This forms the basis for the assumed substitution of eight HEVs for comparably sized gen-sets that we analyze in the text.

Our generic cost model for hybrid HMMWV export power is the same as that for gen-sets, represented by the basic equation in Appendix A. However, in the case of hybrids, we examine the incremental costs of the vehicle relative to a conventionally powered HMMWV and the cost implications of assigning such a vehicle to power export duty where that conflicts with its mobility duties. We first estimate the cost of hybrid export power for our long-term scenario and then for the short-term version.

Long-Term HEV Power Cost

Incremental Depreciation Cost

An HEV is more costly than a conventionally powered vehicle in part because it has an electric motor and an energy storage source such as a battery pack or capacitors in addition to an internal combustion engine. The per unit incremental cost depends on the number of hybrid vehicles acquired: the greater the number, the less the per unit increment.

A conventionally powered HMMWV costs around \$75,000. According to the PM-MEP, the cost to the Army of acquiring hybrid HMMWVs with lead acid batteries would be approximately \$150,000 apiece.[1] Thus, the incremental acquisition cost is about the same as the total cost of a conventionally powered HMMWV, \$75,000.

The depreciation rate on hybrid HMMWVs depends upon the lifetime mileage of such a vehicle. Over the entire Army, average annual truck usage is 3,400 miles. We assume a 25-year life, so that over a HMMWV's lifetime, it travels 85,000 miles.

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[1] Col. Mark Jones, PM-MEP, remarks at the 3rd Annual Conference on Electric Platforms, Washington, DC, March 10, 2003. This price was for a buy of 4,500 vehicles with full hybrid capabilities over 10 years. Other, less capable versions could be constructed at lower cost. On the other hand, the military is hoping to replace lead acid with lithium ion batteries in hybrid vehicles. Lithium ion batteries offer significant logistics savings because they are lighter and smaller than lead acid and last much longer. However, even with expected advances in manufacturing processes these batteries are likely to be far more costly than lead acid. Thus, if lithium ion batteries are eventually used, the incremental cost of full hybrid HMMWVs may be even higher, perhaps over \$100,000 per vehicle.

To calculate a hybrid HMMWV depreciation rate in power export mode, we translate such export into miles driven. A standard HMMWV gets 8 to 10 mpg, depending on its use. The objective for the since-canceled hybrid HMMWV program was to obtain a 30 to 50 percent enhancement in fuel economy, and evidence indicates that the program was achieving this objective.[2] For purposes of this analysis, we assume the hybrid in normal driving mode would get 13.33 mpg. Below we cite evidence that a hybrid HMMWV in power export mode consumes 1.5 gallons/hr of fuel. If fuel consumed is a good proxy for miles driven, then a HMMWV exporting 15 kW of power using 1.5 gallons per hour would "drive" the equivalent of 20 miles in that hour.

If all parts of a hybrid were utilized in power export mode, depreciation would be based on the total costs of the vehicle. However, because such a vehicle is stationary when in that mode, many parts (e.g., axles, suspension, wheels, tires, etc.) would not be subject to stress. For this reason, we base the per mile depreciation rate only on the vehicle's incremental cost (hybrid relative to conventionally powered). Dividing this cost by the vehicle's lifetime mileage, we get \$75,000/85,000, or \$0.8235 per mile. In the long term scenario, in power export mode, the vehicle is "driven" 5,600 hrs × 20 mph = 112,000 miles. Thus, per vehicle depreciation over the mission is 112,000 miles × \$0.8235/mile = \$92,230.

Maintenance

Because the hybrid HMMWV program was discontinued, little empirical data are available with which to estimate the maintenance costs of hybrid HMMWVs. However, companies involved with the production of these vehicles have provided projections of the MTBF of some of that vehicle's main components.[3] Table C-1 shows the projections, which are based on prototype hardware in prototypical applications.

Table C-1. MTBF for Hybrid HMMWV Principal Components

Description	MTBF (hours)
Hybrid vehicle controller	3,078
Power distribution unit	9,929
1.5 L turbo diesel engine	3,227
Generator assembly	34,044
Traction drive motor assembly	15,905

Collectively, the MTBF for this equipment is projected at 1,931 hours, a high number for equipment subject to stress in a battlefield environment. However,

[2] Program Executive Office, Combat Support and Combat Service Support (PEO CS&CSS), briefing slides, March 6, 2003, and presentation at the Hybrid Truck User's Forum, November 2003, Chattanooga, TN.

[3] Personal communication, March 11, 2004.

these are not all the vehicle parts that would be affected and test data are needed to corroborate the numbers. While formal test data have not been made public, the hybrid HMMWV project office stated that a prototype vehicle at Aberdeen Proving Grounds ran 600 hours with but one mechanical failure, a minor one that was rapidly repaired.[4]

These numbers suggest relatively low maintenance costs for a hybrid HMMWV. However, by analogy non-labor maintenance and repair costs for larger gen-sets run about 80 percent of their original acquisition costs, and hybrid HMMWVs are more complex than gen-sets. Given the uncertainty surrounding hybrid HMMWV maintenance, we examine a range of maintenance costs, from 40 to 80 percent of incremental depreciation costs, or \$36,900 to \$73,800.

FUEL

The Program Executive Office, Combat Support and Combat Service Support (PEO CS&CSS) reports that a hybrid HMMWV exporting 15 kW of power over a 3-hour test used 9 percent less fuel than a comparable 15 kW gen-set.[5] However, at rated load, they both consumed at the same rate, 1.5 gallons per hour, and our per unit cost calculations are based on full rated load. As earlier, we assume the cost of fuel in a theater is \$13 per gallon, so the cost of fuel for a hybrid HMMWV operating in power export mode for 5,600 hours would be \$109,200.

PERSONNEL

Running HMMWVs for power export will impose additional wear and tear on the vehicles, and this in turn will require more mechanical services to maintain and repair them. An SBCT carries 27 mechanics, whose responsibilities are to maintain the brigade's 528 wheeled vehicles. In our scenario, vehicles are assumed to average 30 miles per day, or 10,950 miles in a year. Thus, the 27 mechanics are needed to maintain and repair vehicles that total 10,950 × 528 = 5,781,600 miles per year. With power export, however, HMMWVs are assumed to "travel" 5,600 hrs × 20 mph = 112,000 miles. Thus, using a HMMWV in this way adds 1.9 percent to total vehicle miles for an SBCT. Because running a HMMWV in power export mode does not involve all of a vehicle's moving parts, we assume this would require an increase of only 1 percent in maintenance personnel services. Given the number of mechanics assigned, this implies an increase of 0.27 mechanics per hybrid HMMWV used for power export purposes. We assume the same ratio of indirect to direct personnel as for gen-sets. This implies an increase of 0.43 indirect personnel in addition to the 0.27 direct for an HEV.

We cost an HEV mechanic at the level of an E-4, the average for gen-set operators in an SBCT. Total compensation per year for an E-4 is about \$46,000, so the additional cost per HMMWV is \$12,400. The indirect personnel is costed at the

[4] Steve Roberts, Deputy Product Manager, Hybrid HMMWV Office, PEO CS CSS, oral communication, August 19, 2003.

[5] See Note 3.

all-Army average of $52,200, implying an additional cost of $22,400. Thus, the total cost of personnel over the 1-year scenario is estimated at $34,800 per hybrid HMMWV.

Transport

Since a hybrid vehicle propels itself, no cost is added to move its power export capability from one part of a battlefield to another. However, hybrids are heavier than conventionally powered HMMWVs and therefore impose an incremental cost to move them to a battlefield. According to the hybrid HMMWV project office, the increment in gross vehicle weight is 600 lb.[6] This implies the following per vehicle incremental transport costs for our scenario:

- Air—$2300
- Sea—$50
- Preposition—$180.

Backup Power

We assume one 5 kW and one 10 kW APU are assigned to back up a HMMWV. Given their unit cost, the cost of capital for 1 year at 7 percent for such backup is $2,570, while the transport cost is $3940 by air, $85 by sea, and $310 with prepositioning. Thus, total costs of backup are $6,510 by air, $2,655 by sea, and $2,880 with prepositioning.

Mobility

Mobility costs arise where the use of a HMMWV in power export mode prevents its use in some other application. Sometimes such a vehicle would not have been needed for anything else, in which case no mobility cost is associated with power export. However, where other uses are foreclosed, such a cost exists.

We estimate this cost in terms of the incremental HMMWV capability that must be acquired to maintain a constant level of mobility. Thus, for example, if the use of a HMMWV in power export mode would reduce its use in other applications by 2 hours, then the mobility cost would be the cost of 2 hours of HMMWV services.

This mobility cost has three parts: the acquisition cost of another HMMWV, the cost of bringing it to the battlefield, and the cost of its driver. The costs of running the vehicle, that is fuel, maintenance, etc., would have been incurred in any case and so are not part of the mobility cost of using a HMMWV for power export purposes.

[6] Hybrid Electric Truck Users Forum, briefing, Indianapolis, IN, January 22, 2002.

As previously stated, the acquisition cost of a HMMWV is approximately \$75,000, and its assumed lifetime mileage is 85,000 miles. This implies a depreciation rate of \$0.8235 per mile. If we assume that the HMMWV would have traveled 20 miles per day during the time it is in power export mode, then its replacement would travel 7,300 miles annually, at a cost of about \$6,000.

A standard HMMWV weighs approximately 11,500 pounds. Given our assumed scenario, this implies transport costs as follows:

- Air: 8,700 miles × \$0.856/ton mile × 5.75 tons = \$42,820
- Sea: \$160/short ton × 5.75 tons = \$920
- Preposition: \$920 + 500 miles × \$0.856/ton mile × 5.75 tons = \$3380

Finally, over the year we assume the conflict between power export and mobility for a HMMWV averages 2 hours per day, or 730 hours in all. We cost the driver at the E-3 rate of \$39,000 per year. Assuming the E-3 would be engaged 16 hours per day in a combat theater, the total cost is one-eighth of \$39,000 or about \$4900.

From this, the mobility cost of using a hybrid HMMWV for power export purposes in the one-year scenario depends greatly on the mode of transport to bring it to a theater. By air it would be almost \$54,000 but by sea total mobility cost is only about \$12,000.

Total Cost

The various cost elements and the total are shown in Table C-2.

Table C-2. Hybrid HMMWV Power Total Costs (Long-Term Scenario)

Cost category	Amount (\$000)
Incremental depreciation	92
Maintenance	37–74
Fuel	109
Personnel	35
Transport on battlefield	Not applicable
Transport to battlefield	
Air	2
Sea	—[a]
Preposition	—[a]
Backup Power	
Air	6
Sea	3
Preposition	3

Table C-2. Hybrid HMMWV Power Total Costs (Long-Term Scenario) (Continued)

Cost category	Amount ($000)
Mobility	
Air	54
Sea	12
Preposition	14
Total	
Air	335–372
Sea	288–325
Preposition	290–327

[a] Under $500.

Table C-2 shows the costs of generating power from a single hybrid HMMWV for 1 year under our assumed scenario parameters. If mobility cost is excluded, the numbers would drop to around $270,000 apiece. For eight hybrid electric vehicles, the totals would be eight times the numbers shown.

Table C-3 shows the cost of power expressed in kWh. These assume that 15 kW of export power is produced for 5,600 hours (15 kW × 5,600 = 84,000 kWh). The numbers shown range from about $3.45 to $4.40 per kWh. These are roughly $1.50 to $2.25 per kWh higher than those for gen-sets in the long-term scenario.

Table C-3. Hybrid HMMWV Power Unit Costs (Long-Term Scenario)

Transport mode	$/kWh
Air	3.99–4.43
Sea	3.43–3.87
Preposition	3.45–3.89

Short-Term HEV Power Cost

For our purposes, the principal difference between the long- and short-term combat scenarios is the number of hours of power export. Also, in the short-term scenario we assume no conflict between power export and mobility, so the mobility cost is zero. This latter assumption rests on the notion that less power export is required in the short term, when combat is more intense and U.S. forces are on the move.

Depreciation

The total power requirement in the short-term scenario is 240 hours (30 days × 8 hours). Given our inference that an hour of power export is equivalent to 20 miles driven, this amounts to 4,800 miles over the 1-month duration. At $0.8235 per mile, total depreciation cost is $3,950.

Incremental Maintenance

At 40 to 80 percent of initial acquisition cost, maintenance in the short-term scenario would be $1,580 to $3,160.

Fuel

Over the time frame of the short-term scenario, a hybrid HEV would operate 240 hours and utilize 1.5 gal/hr. At $13/gal, this implies a fuel cost of $4,680.

Personnel

Over a 1-month scenario, personnel costs would be one-twelfth the total of the long-term scenario, or $5,310.

Transport

Transport costs would be unchanged from the long-term scenario.

Backup Power

The cost of backup power is reduced in the short-term scenario because capital is tied up for a shorter period. Total costs, including transport to the battlefield of the backup, are $4,155 if by air, $200 by sea, and $525 with prepositioning.

Mobility

Under our assumptions, there is no mobility cost of HEV power export during the 1-month scenario.

Total Cost

Table C-4 shows the total costs of hybrid HMMWV export power in the short-term scenario.

Table C-4. Total Costs of Hybrid HEV Power Export (Short-Term Scenario)

Cost Category	Amount ($000)
Incremental depreciation	4
Maintenance	2–3
Fuel	5
Personnel	3
Transport Air Sea Preposition	 2 —[a] —[a]
Backup power Air Sea Preposition	 4 —[a] —[a]
Total Air Sea Preposition	 20–21 14–15 15–16

[a] Under $500

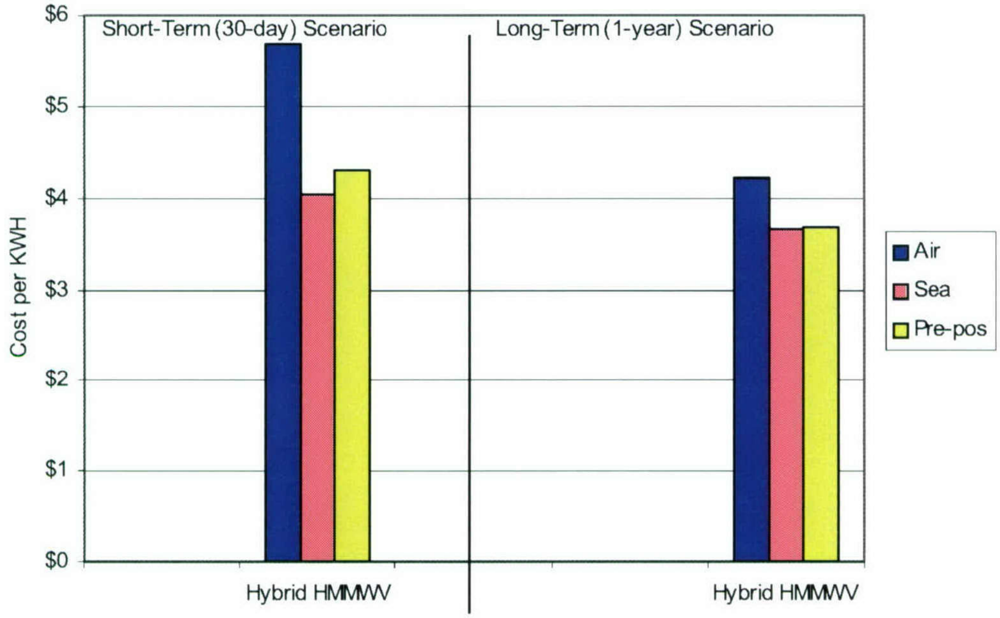
Over the 30-day period, a hybrid HMMWV would export 240 hr × 15 kW, or 3,600 kWh. Table C-5 shows the $-per-kWh costs.

Table C-5. Hybrid HMMWV Power Export Unit Cost (Short-Term Scenario)

Transport Mode	$/kWh
Air	5.56–5.83
Sea	3.89–4.17
Preposition	4.17–4.44

Total costs of HEV export power are much less in the short-term scenario than in the long term, but unit costs are greater. Unit costs rise because some costs are fixed, such as transport to the battlefield, so the shorter the scenario is, the higher the per-kWh cost from this factor. Figure C-1 uses mid-points of the ranges of Tables C-3 and C-5 to display costs per unit of power for a single hybrid HMMWV for the long-term and short-term scenarios.

Figure C-1. Costs of Hybrid HMMWV Power Export



Appendix D. Cost Comparison—Hybrid HMMWVs and 15 KW Gen-Sets

Long-Term Scenario

Table D-1 summarizes the total costs of eight hybrid HMMWVs and eight 15 kW gen-sets in the long-term scenario. Below we explain the derivation of these numbers.

Table D-1. Power Cost for Eight Hybrid HMMWVs and Eight 15 KW Gen-Sets (Long-Term Scenario)

Cost category	HMMWVs ($000)	15 kW gen-sets ($000)
Depreciation	738	102
Maintenance and repair	295–590	165
Fuel	874	874
Personnel	280	80
Transport to battlefield		
Air	18	130
Sea	—	3
Preposition	1	10
Backup power		
Air	6	6
Sea	3	3
Preposition	3	3
Mobility cost		
Air	144	—
Sea	60	—
Preposition	65	—
Total		
Air	2,355–2,650	1,357
Sea	2,250–2,545	1,227
Preposition	2,256–2,551	1,234

Gen-Sets

Depreciation

The eight 15 kW gen-sets consist of five trailer-mounted and three power units. We estimate depreciation cost by dividing the aggregate acquisition cost of these eight units ($170,400) by their lifetimes in hours (9,375 hours) and multiplying by 5,600 hours, the operating period during the long-term scenario. This results in estimated costs of $101,800.

Maintenance

Maintenance and repair costs are estimated by taking the annual maintenance cost for a 15 kW gen-set ($1,383), multiplying by 8, calculating an hourly rate based on a 375-hour year, and then multiplying by 5,600 hours. The result is an estimated cost of $165,200.

Fuel

Fuel costs reflect the hourly consumption rate of eight 15 kW generators (12 gallons per hour) multiplied by the cost of fuel ($13 per gallon) multiplied by 5,600 hours. We estimate fuel costs at $873,600 over the 1-year period.

Personnel

Personnel costs are assumed to be equal to the proportion of an SBCT's gen-sets made up by the eight 15 kW units (8/146) multiplied by the aggregate personnel cost assigned to generator repair and maintenance ($1,459,800). The result is an estimated cost of $80,100.

Transport to Battlefield

Transport is estimated by taking the aggregate weight of the eight 15 kW gen-sets and calculating the air, sea, or prepositioning costs for the long-term scenario using the rates cited in Appendix A.

Backup Power

We assume that a combination consisting of one 5 kW APU and one 10 kW APU provides sufficient backup power for the eight 15 kW gen sets. Costs for this combination are as in Appendix C for a single hybrid vehicle capable of exporting 15 kW of power.

HMMWVs

Depreciation

We assume that depreciation is eight times the depreciation shown for a single HMMWV in Appendix C. We therefore estimate depreciation costs at $737,800.

Maintenance and Repair

We assume that maintenance and repair costs are eight times those shown for a single HMMWV in Appendix C. We therefore estimate them at $205,200 to $590,400.

Fuel

Fuel costs are eight times those of a single HMMWV producing 15 kW of power over 5,600 hours. As with the single HMMWV, there is a range of costs from 90 to 100 per cent that of eight 15 kW gen-sets.

Personnel

In Appendix C, we estimated that the total cost of direct and indirect personnel to maintain a single HMMWV over a year in our scenario was $35,000. We assume the cost for eight HMMWVs is eight times this cost, or $280,000.

Transport to Battlefield

We assume transport to the battlefield for eight HMMWVs as eight times that for a single HMMWV.

Backup Power

As with the eight 15 kW gen-sets, we assume that a combination consisting of one 5 kW and one 10 kW APU is sufficient to back up the eight HMMWVs. Appendix C explains the costs of this combination.

Mobility

In Appendix C, we estimated mobility costs on the assumption that an additional HMMWV would be transported to the theater and operated 2 hours per day to make up for a HMMWV tied up in power export. For present purposes, we assume that two HMMWVs can make up for the assumed loss of mobility from using eight such vehicles for power export. Thus, we include transport and driver costs for two HMMWVs plus eight times the depreciation shown for a single HMMWV in Appendix C.

Table D-2 summarizes the per unit cost results for the long-term scenario.

Table D-2. Power Cost for Eight Hybrid HMMWVs and Eight 15 KW Gen-Sets ($ per kWh) (Long-Term Scenario)

Transport Mode	HMMWVs	Gen-sets
Air	3.50-3.94	2.02
Sea	3.35-3.79	1.83
Preposition	3.36-3.80	1.84

Short-Term Scenario

Table D-3 summarizes the total costs of eight hybrid HMMWVs and eight 15 kW gen-sets in the short-term scenario.

Table D-2. Power Cost for Eight Hybrid HMMWVs and Eight 15 KW Gen-Sets (Short-Term Scenario)

Cost category	HMMWVs ($000)	15 kW gen-sets ($000)
Depreciation	32	4
Maintenance and repair	13–25	7
Fuel	37	37
Personnel	22	7
Transport to battlefield		
Air	18	130
Sea	—	3
Preposition	1	10
Backup Power		
Air	4	4
Sea	—	—
Preposition	1	1
Total		
Air	127–139	191
Sea	105–117	60
Preposition	107–119	68

For the short-term scenario, we again analyze the consequences of substituting eight hybrid HMMWVs for eight 15 kW gen-sets for an SBCT. In this case, we assume there are no mobility costs for hybrid HMMWVs (that is, there is no conflict between their power export and mobility duties in the first 30 days of combat). We assume further than the backup power needed for the short-term scenario is the same as that for the long term, so the same transport costs (though not the same capital costs) pertain.

Gen-Sets

We derive the costs of gen-sets in the short-term scenario similarly to those for the long term. We calculate hourly costs for depreciation, maintenance, and fuel use and then multiply them by the number of hours gen-sets are assumed to operate in 1 month, 720. Personnel costs are one-twelfth those in 1 year, and costs of transport to the battlefield are the same. We adjust costs of backup power for the shorter time. Table D-3 shows the results.

HMMWVs

Given our assumptions, the costs of adding eight hybrid HMMWVs are eight times those of adding a single HMMWV, except for the backup power, which we assume remains the same as for a single HMMWV. Table D-3 shows the results.

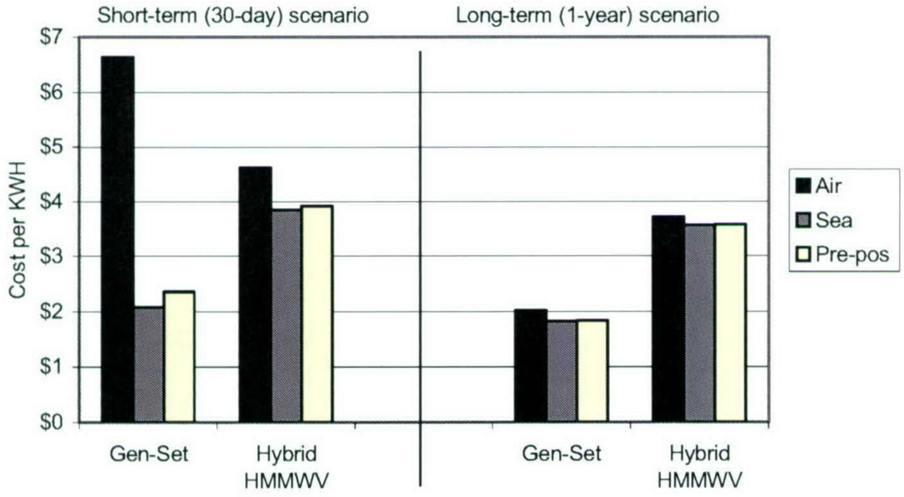
The cost of transporting gen-sets to the battlefield dominates these numbers. If power is brought to the battlefield by air, hybrid HMMWVs would be the less expensive alternative, whereas if sea or prepositioning is used, the opposite is true, that is, gen-sets are less expensive. This is evident also in Table D-4, which shows the $-per-kWh costs of power for the short-term scenario.

Table D-4. Power Cost for Eight Hybrid HMMWVs and Eight 15 KW Gen-Sets ($ per kWh) (Short-Term Scenario)

Transport Mode	HMMWVs	Gen-sets
Air	4.41–4.83	6.63
Sea	3.64–4.06	2.08
Preposition	3.71–4.13	2.36

Figure D-1 summarizes the information in Tables D-2 and D-4. The bars for the HMMWVs represent mid-points of the ranges of costs shown in the two tables.

Figure D-1. Power costs for Eight Hybrid HMMWVs and Eight 15 KW Gen-Sets ($ per kWh) (Short-Term and Long-Term Scenarios)



Appendix E. Uncertainties of the Analysis

Our analysis is predicated on a number of assumptions, some of which may importantly affect the conclusions we have reached. We divide the discussion of the uncertainties of the analysis into four separate parts; gen-sets, hybrid HMMWVs, the scenario we have chosen, and other factors.

Gen-Sets

As discussed in the text and in Appendix A, we are uncertain as to the useful lifetime of a gen-set. The expectation is that a gen-set will operate 375 hours per year for 17 years or 6375 hours before replacement, but budget constraints apparently force many of them to operate for up to 25 years at 375 hours per year or 9375 hours, and we use the latter number in our analysis. In the long term scenario, the range of uncertainty is $.08 per kWh. Relative to the mean, this range is plus or minus two percent.

We are uncertain as to the number of hours that soldiers must spend repairing and maintaining gen-sets in an operating environment. We used the TOE for an SBCT as our source of data on this issue, but experience in Iraq and elsewhere could indicate different numbers of soldiers required than the 12 direct personnel we assumed. A one-soldier change in direct requirement, for example, would result in a 1 percent change in the total costs of providing power via gen-sets to an SBCT.

Our analysis assumed that only SBCT gen-sets of 15KW capacity or above would be mounted on trailers. However, if some of the unit's 5KW and 10KW gen-sets were also so mounted, that would increase the total weight and space required to transport the gen-sets to the battlefield and within it. A 3/4 ton trailer, for example, weighs 1460 lbs and takes up a few hundred cubic feet of space.[1]

Existing TQGs have a long history and their performance and cost is fairly well established. Performance and cost parameters for the next generation of gen-sets, however, are far from assured. We used performance objectives established by the Army for AMMPS gen-sets in our analysis, but these might not be attained in practice, and their cost might be different from the 15 percent acquisition cost increment over TQGs that we assumed. Gen-set technology has been improving over time, however, so that it seems likely some further improvement will occur.

Hybrid HMMWVs

Because there is little published data on the performance of hybrid HMMWVs, we have been compelled to make a number of assumptions about their cost and

[1] One way to deal with this is to mount a gen-set directly upon the bed of a vehicle. According to Mr. Tim Raney, DCD-Ordnance, CASCOM, some Army units have used this technique to permanently mount 10 kW gen-sets onto the backs of HMMWVs (personal communication, August 30, 2004).

performance. In particular, we used an estimated incremental acquisition cost of \$75k for the purchase of 4500 vehicles over 10 years. This cost estimate assumed the use of lead acid batteries, which are heavier and less long lasting than other battery technologies such as nickel metal hydride or lithium ion, but also less expensive. Lithium ion batteries in particular could cost as much as \$60k per vehicle even if production cost reduction objectives are met.[2] This suggests a higher incremental cost per hybrid HMMWV than assumed in our analysis.

Though hybrid technologies have been used in passenger cars for several years, their application in Army vehicles is in its early stages. Thus, there is considerable uncertainty about the cost of maintaining hybrid vehicles in a combat environment. We assumed a range of lifetime maintenance costs of from 40 to 80 percent of incremental acquisition cost. In our analysis of the costs of power from a single hybrid HMMWV, this imparted a range for total costs relative to the mean of plus or minus 5 percent.

We also have little information on the useful lifetime of a hybrid HMMWV. In our analysis we assumed such a hybrid would travel 3400 miles per year for 25 years or 85,000 miles in all. If true expected lifetime mileage is different from this, then the cost of power from this source would be different as well.

Scenario

Chart 1 in the text shows the behavior of power costs in the short-term and long-term scenarios. This chart indicates that duration of the mission has a very substantial effect on power costs.

There are many other scenarios which might be chosen. These could vary not only in duration, but also in the number of hours per day that export power is required, the number of hours per day that mobility assets are needed for transport purposes and how much power is required at different times of the day and night. Experience in Iraq and Afghanistan might provide useful data on this question.

We assumed that mobility requirements would constrain the availability of hybrid HMMWVs for export power duties in the long-term scenario but not in the short-term. This added roughly 4-15 percent to costs in the long-term scenario, but nothing to costs in the short-term. Different assumptions about such conflicting needs would change the relative attractiveness of hybrid HMMWVs as a power source, particularly in the short-term scenario, where it is very expensive to transport any additionally required mobility assets to the theater.

There is uncertainty about mode of transport to and within the battlefield. We showed ranges of costs dependent upon whether air, sea or prepositioning of equipment is used, and saw that these affected total costs by several percent. For example, costs of gen-set power for an SBCT ranged with transport mode about 4

[2] Presentation by SAFT Co., U.S. Army Power & Energy Integrated Product Team conference, January 12, 2004.

percent relative to the mean. No estimate was made for costs of C130 transport within a battlefield as we did not include this mode of transport in our scenario, but such transport likely would favor hybrid HMMWVs over gen-sets because of weight differences and this would close the cost gap between the two technologies.

Army Planning Factors

We used a number of Army planning and cost factors in our analysis. For example, we assumed that the theater of operations would be 8700 miles from the U.S., with present costs of air and sea shipment. These assumptions directly affect transport costs. If the theater were closer to the U.S. transport by air would be less costly and the relative advantage of hybrid vehicles would be smaller. Experience in Iraq, Afghanistan and elsewhere may result in changes to the planning factors that could have a bearing on our findings.

Average vs. Marginal Costs of Fuel

Our analysis shows that fuel costs are a major component of the cost of export power in all of the scenarios and with all of the technologies we examined. The estimated per gallon cost that we used, $13, was taken from an independent source and represents the total cost, including underlying logistics network, of delivering fuel to a battlefield. However, for the short run this is likely an average cost, not a marginal cost. If so, the short run cost savings from fuel economy in battlefield power production would be less than we have shown. For example, if the direct cost of fuel is $2.00 per gallon and the logistics assets necessary to move that fuel to the battlefield do not change in the short term with small reductions in use, then short-term cost savings are $2.00 per gallon. However, over the longer term we assume the Department of Defense will size the logistics network needed to provide fuel on the battlefield to the amount shipped, and therefore $13 per gallon is appropriately treated as a long-run marginal cost estimate.